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DEPTH OF FOCUS DISCRIMINATION BY CRUSTAL
PHASES FOR NTS NUCLEAR EXPLOSIONS

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ABSTRACT

Time residuals for Pg-Pn intervals as a function of epicentral distance and Sg-Pg intervals are examined for "calibrated" source-to-recording-station paths. At some stations it is found that the residuals are reduced by about one-half when true epicentral distance is used. Depths of foci for 16 nuclear explosions are estimated from Pg-Pn residuals. When the average is taken for depth estimates from three or more recording stations, the results are within 10 km of the surface. Depths computed from single stations may be as much as 30 km in error. The greatest source of error is in reading arrival times of the Pg phase with sufficient accuracy from LRSM three-component recordings.

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DEPTH OF FOCUS DISCRIMINATION BY CRUSTAL PHASES FOR NTS NUCLEAR EXPLOSIONS.

I. INTRODUCTION

Several investigators commented on H. I. S. Thirlaway's suggestion that crustal phases should be used for focal depth discrimination.[1] Some suggestions for improving the method were:

(1) Pg-Pn time intervals should be considered as a function of epicentral distance rather than as a function of Sg-Pg time intervals.

(2) Calibration would be necessary to obtain reliable results in regions where crustal structure is complicated.

(3) More than one station should be used to estimate any given focal depth.

(4) Phase identification must be improved to make the method reliable.

The Pg and Sg phases are compression-rarefaction and shear waves, respectively, that travel a "direct" path through the crust. Pn is a compression-rarefaction diffracted or "head wave" from the M discontinuity between the crust and mantle. The discussion that follows examines the first three suggestions using data collected by the Long Range Seismic Measurements (LRSM) teams. The need for the improvement called for by the fourth suggestion is obvious from the results presented.

A similar study has been made by Herrin and Taggart.[2] Although their results agree with those presented here, their basic method of approach was slightly different. They attempted to determine how well the depth of focus could be estimated with a calibration shot of about one-tenth the yield of a given event.

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[1] "A consideration of H. I. S. Thirlaway's 'Depth of Focus Discrimination Within the Crust at First-Zone Distances'," VESIAC Special Advisory Report, Nov. 1, 1961.

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II. SELECTION OF DATA

The data were taken from seismograms included in LRSM shot reports. All Nevada Test Site (NTS) events for which at least three readable seismograms were available were considered. The seismograms were arbitrarily divided into two groups. Those in the first group were from shots for which the reports are unclassified and were used to establish a path "calibration" between NTS and the recording station. Seismograms in the second group were from shots for which the reports are classified and were used to test the path "calibration."

The author read all seismograms at one time before any calculations were begun. An attempt was being made to see how consistently one investigator could read these arrival times with a "single look" at the seismograms. Once the seismograms were read for the Pn, Pg, and Sg arrival times, they were not reviewed to see if a reasonable change in arrival time would be more consistent with the rest of the data. Arrival times from the LRSM reports were not used since some of these reports do not list arrival times for the Pg and Sg phases. The usual difficulties were encountered in finding the beginning of the Pg and Sg phases. A large portion of the time residuals can be attributed to inability to read the true beginning of these phases. In some cases the signal-to-noise ratio was poor for Pn arrivals. Errors up to 3 sec are evident in the Pg-Pn time intervals. The errors in Sg-Pg time intervals are even larger. Table I lists values for epicentral distance, Δ, and the time difference, Pg-Pn, and Sg-Pg for each station and event used for path "calibration." Table II gives the values of Δ and Pg-Pn for each station and event used as independent data to check the "calibration." Code names or dates for explosions have not been listed to obviate classifying this paper.

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The stations are those for which seismograms are most commonly included in LRSM reports. Although the stations were selected for convenience rather than in accordance with any plan, the data represent a fair coverage of azimuths and distances. The stations for which path calibrations from NTS were obtained are as follows:

Site Designation	Site Location
LCNM	Las Cruces, New Mexico
DRCO	Durango, Colorado
WINV	Winnemucca, Nevada
CPCL	Campo, California
FSAZ	Flagstaff, Arizona
FMUT	Fillmore, Utah
MNNV	Mina, Nevada

III. METHOD OF ANALYSIS

The first portion of this study was made in accordance with the method suggested by Thirlaway. To obtain a path "correction," the travel-time curves for Pg, Sg, and Pn were assumed to be represented by the following straight lines:

$$
\left.
\begin{aligned}
Pg &= \frac{1}{u_1} \, \Delta \\[1em]
Sg &= \frac{1}{V_1} \, \Delta \\[1em]
Pn &= \frac{1}{u_2} \, \Delta + C
\end{aligned}
\right\} \quad (1)
$$

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$$\left.\begin{aligned} Pg &= \frac{1}{u_1}\Delta \\[4pt] Sg &= \frac{1}{V_1}\Delta \\[4pt] Pn &= \frac{1}{u_2}\Delta + C \end{aligned}\right\} \tag{1}$$

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where

u_1 = Pg velocity

u_2 = Pn velocity

V_1 = Sg velocity

Δ = epicentral distance

C = time intercept of Pn travel-time curve

From Eqs. (1),

$$Pg - Pn = (Sg - Pg)\left(\frac{V_1}{u_2}\right)\left(\frac{u_2 - u_1}{u_1 - V_1}\right) - K. \qquad (2a)$$

Assuming u_1 = 6 km/sec, u_2 = 8 km/sec, and V_1 = 3.5 km/sec, Eq. (2a) becomes

$$Pg - Pn = 0.35 (Sg - Pg) - K \qquad (2b)$$

Here, K denotes the Pn intercept to distinguish it from C obtained from Pg - Pn as a function of distance. K is obtained when Pg - Pn is considered as a function of Sg - Pg time intervals. No great physical significance is attached to K (or C) since the velocities are only approximate. Values of K can be computed for each set of observations of (Pg - Pn) and (Sg - Pg) at each of the stations. The average of all computed values for K from each station was taken as the most probable value. Residuals from this average value for each station are shown in Fig. 1. The large scatter indicates that the phases Pg and Sg were not read with sufficient accuracy to be useful for depth-of-focus discrimination.

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The second portion of this study was made using Pg - Pn time intervals as a function of distance rather than as a function of Sg - Pg time intervals. From Eqs. (1)

$$Pg - Pn = \left(\frac{1}{u_1} - \frac{1}{u_2} \right) \Delta - C \qquad (3a)$$

and for the velocities being considered Eq. (3a) becomes

$$Pg - Pn = \frac{1}{24} \Delta - C \qquad (3b)$$

Values for Δ were taken from the true epicentral distances. The Pn intercept, C, was computed for each seismogram, and the average values of C for each station were obtained. As with K, the intercept, C, is a function of (1) the depth (taken as zero), (2) the crustal structure under the source and the recording station, and (3) the velocities along the paths in the crust and upper mantle. While an oversimplified model has been assumed, the slope of the Pg - Pn vs. Δ curve is sufficiently accurate within the limited distance range for events considered at each station. The average value of C for each station and the corresponding residuals for individual observations are shown in Fig. 2. The probable errors are based on insufficient samples, but are consistently about $\pm$ 1 sec. This magnitude of error would correspond to about 10 km in focal depth. Individual errors are as large as 3 sec or amount to nearly 30 km error in focal depth determination.

The question still remains as to how well the errors in Pg-Pn will average to zero when several stations are used for an individual shot. Table III lists the estimated depths obtained from Pg - Pn time residuals, δt. These depth estimates are obtained from the relation

$$\delta t = (Pg - Pn)_o - (Pg - Pn)_h = \overline{C} - C_h = C_o - C_h$$

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Here C_h is the Pn intercept for a focal depth, h, and $\tilde{C}$ is assumed to be the Pn intercept for zero focal depth, or C_0. For a single-layer, constant-velocity crust where

$$C_h \approx (2H-h) \left[\left(\frac{1}{u_1}\right)^2 - \left(\frac{1}{u_2}\right)^2 \right]^{1/2} .$$

For zero depth,

$$C_0 = 2H \left[\left(\frac{1}{V_1}\right)^2 - \left(\frac{1}{u_2}\right)^2 \right]^{1/2} .$$

The velocities used here give the depth in kilometers as

$$h \approx 9.1 \, \delta t. \qquad\qquad (4)$$

The range of depths obtained from Eq. (4) by use of the residuals, t, range from +25 km to -27 km. Positive values are below the surface and negative values are above the surface. When the depths for a single event are averaged from the data of several stations, they give results within 10 km of the surface.

Table IV compares the average depths obtained by the Pg - Pn method with the depths obtained from the computer program that located the epicenters. It is quite obvious that the crustal phases give a more reliable estimate of depth than was obtained by the computer program. The accuracy, however, is only sufficient to place the source in the upper or lower portion of the crust when several stations are used. If only one station is available, all that can be said is that the event is intercrustal or subcrustal from the presence or absence of crustal phases.

IV. CONCLUSIONS

Depth-of-focus determinations by use of Pg and Pn phases increase in reliability with "calibration" of paths and with averaging solutions from several recording stations. The degree of improvement is limited by inability to read the time of arrival of the Pg phase with sufficient accuracy. Improved methods of identification of this phase from standard three-component recordings are needed. Under idealized conditions, such as existed in obtaining the data used here, it is possible to determine that the focus was in the upper or lower portion of the crust.

TABLE I

VALUES OF Δ, PG-PN, SG-PG USED FOR PATH "CALIBRATION"

Station	Event	Δ(km)	Pg-Pn(sec)	Sg-Pg(sec)
LCNM	1	1017	33.3	132
	3	1005	28.8	125
	5	1013	31.2	124
	6	1005	29.3	121
	7	1009	31.8	121
	8	1006	32.0	129
	10	1006	33.0	127
DRCO	1	734	22.8	86
	2	735	23.1	85
	3	733	24.6	91
	7	733	24.1	95
	8	733	25.0	90
	9	747	21.8	84
	10	733	20.4	87
CPCL	1	500	13.1	56
	2	488	14.4	56
	3	480	16.5	55
	4	454	11.5	54
	6	479	15.1	52
	7	488	15.1	57
	8	481	12.5	57
	9	495	16.0	55
	10	480	12.8	53
WINV	1	474	15.5	54
	2	485	16.1	58
	3	495	14.9	59
	5	479	14.6	55
	6	494	14.9	62
	7	486	17.6	53
	8	492	13.0	64
	10	494	13.6	59
FSAZ	2	485	11.9	56
	3	478	11.4	54
	6	478	10.6	58
	7	483	13.0	56
	9	500	10.5	58
	10	479	10.2	58

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TABLE I
(Continued)

Station	Event	Δ (km)	Pg-Pn(sec)	Sg-Pg(sec)
FMUT	1	403	12.1	44
	2	410	14.1	45
	3	412	10.6	48
	4	423	10.8	53
	5	405	11.5	45
	6	412	10.8	48
	7	409	10.1	47
	9	417	14.2	43
	10	414	10.4	50
MNNV	1	228	2.6	39
	2	235	1.5	30
	3	242	2.7	34
	4	267	4.0	34
	5	232	3.1	30
	6	243	2.7	33
	7	236	3.0	31
	9	220	2.2	28
	10	242	2.6	30

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TABLE II

VALUES OF Δ AND PG-PN USED TO TEST PATH "CALIBRATION"

Station	Event	Δ(km)	Pg-Pn (sec)
LCNM	11	1005	30.7
	13	1011	31.3
	14	1012	32.0
	15	1017	34.0
	16	1005	29.4
DRCO	11	733	20.9
	13	734	22.0
	14	734	23.7
	15	749	23.5
CPCL	11	479	12.7
	13	490	14.6
	14	490	12.7
	15	475	11.6
	16	480	12.8
WINV	11	494	13.8
	12	494	14.2
	13	484	15.3
	14	482	13.3
	15	494	15.0
	16	494	12.3
FSAZ	11	478	12.0
	15	491	12.8
FMUT	11	413	10.7
	12	413	10.8
	13	409	11.4
	14	408	12.5
	15	428	13.5
	16	413	11.0
MNNV	11	243	2.0
	12	242	2.8
	13	235	2.3
	14	234	2.7
	15	234	3.0
	16	242	2.6

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TABLE III

DEPTHS[a] ESTIMATED FROM INDIVIDUAL SEISMOGRAMS

				Station			
Event[b]	LCNM	DRCO	CPCL	WINV	FSAZ	FMUT	MNNV
1	+14	- 3	-16	+ 9	---	+ 7	+ 3
2	---	0	+ 1	+12	+ 6	+24	-10
3	-22	+14	+23	- 4	+ 5	- 9	- 2
4	---	---	- 6	---	---	-11	+ 1
5	+ 3	---	---	+ 2	---	+ 2	+ 6
6	-19	---	+10	- 4	- 3	- 7	- 2
7	+ 4	+ 9	+ 7	+25	+17	-12	+ 4
8	+ 7	+17	-14	-20	---	---	---
9	---	-16	+13	---	-12	+12	+ 3
10	+16	-25	-18	-16	- 7	-11	- 3
11	- 5	-20	-14	-11	+10	- 8	- 8
12	---	---	---	-10	---	-11	- 1
13	- 2	-10	+ 5	+ 4	---		+ 1
14	+ 5	+ 5	-15	-13	---	+10	+ 1
15	+21	- 2	-20	- 3	+13	+12	+ 4
16	-16	---	-11	-27	---	- 5	- 3

[a] Depths are given in kilometers. The numerical values depend on the simple crustal model used in this study. Changes in this model will change the computed depths slightly.

[b] Events 1-10 were used in path "calibration."

TABLE IV

AVERAGE DEPTHS COMPUTED FROM PG-PN AND DEPTHS FROM LRSM REPORTS

Event[a]	Pg-Pn Depth (km)	No. of Stations	LRSM Depth (km)	No. of Stations
1	+2	6	+75	10
2	+6	6	+61	7
3	+1	7	Surface	15
4	-5	3	Not Computed	--
5	+3	4	+122	6
6	-4	6	Surface	16
7	+7	7	Surface	23
8	0	4	+162	7
9	+2	5	+27	4
10	-9	7	+43	22
11	-8	7	+43	7
12	-7	3	Zero[b]	4
13	0	6	Surface	9
14	-1	6	+43	12
15	+4	7	+75	5
16	-5	5	+114	6

[a] Events 1-10 were used in path "calibration."

[b] Constrained to zero by computer program.

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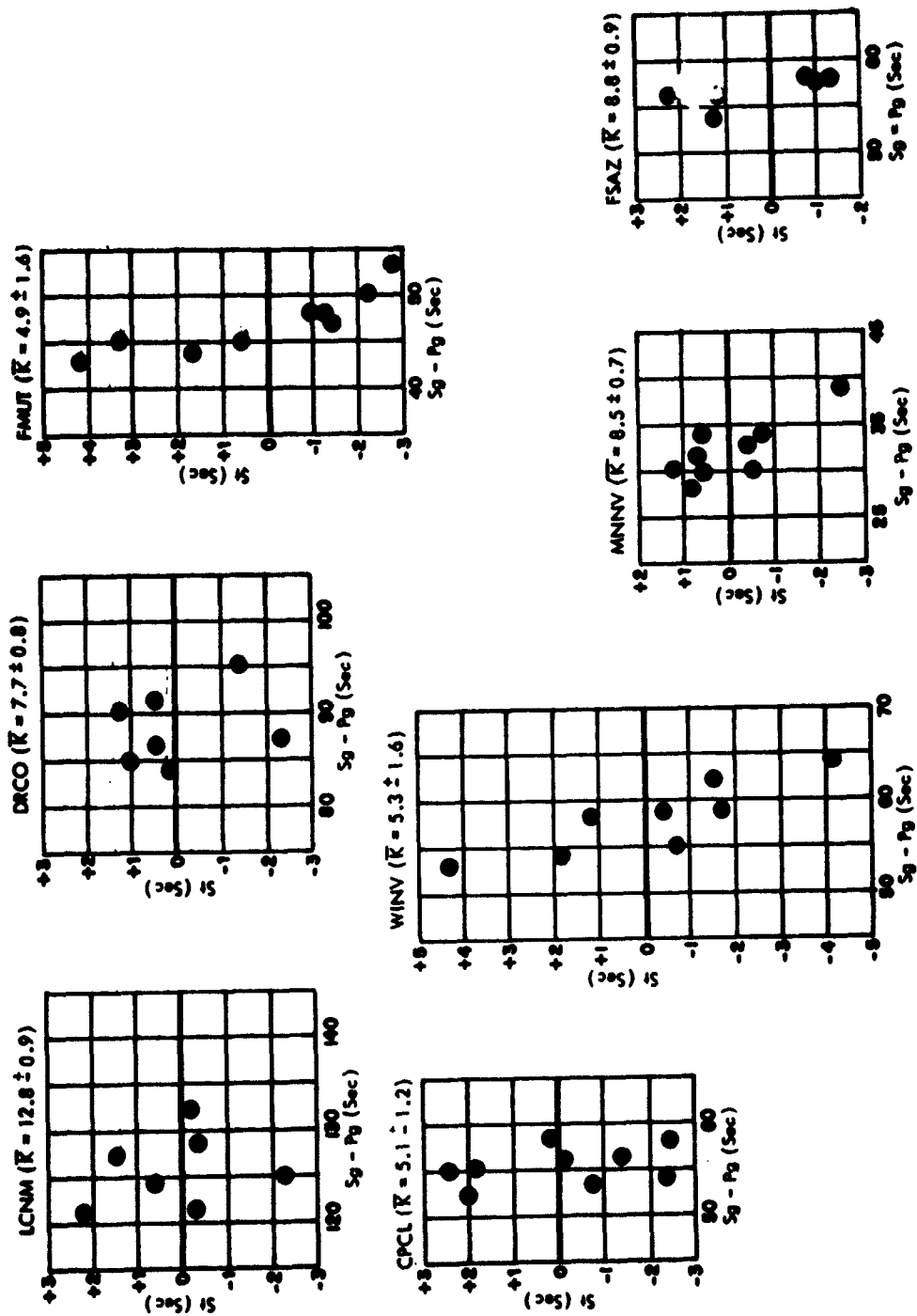
FIGURE 1. Pg-Pn Residuals from Average as a Function of Sg-Pg. $\overline{K}$ is obtained from

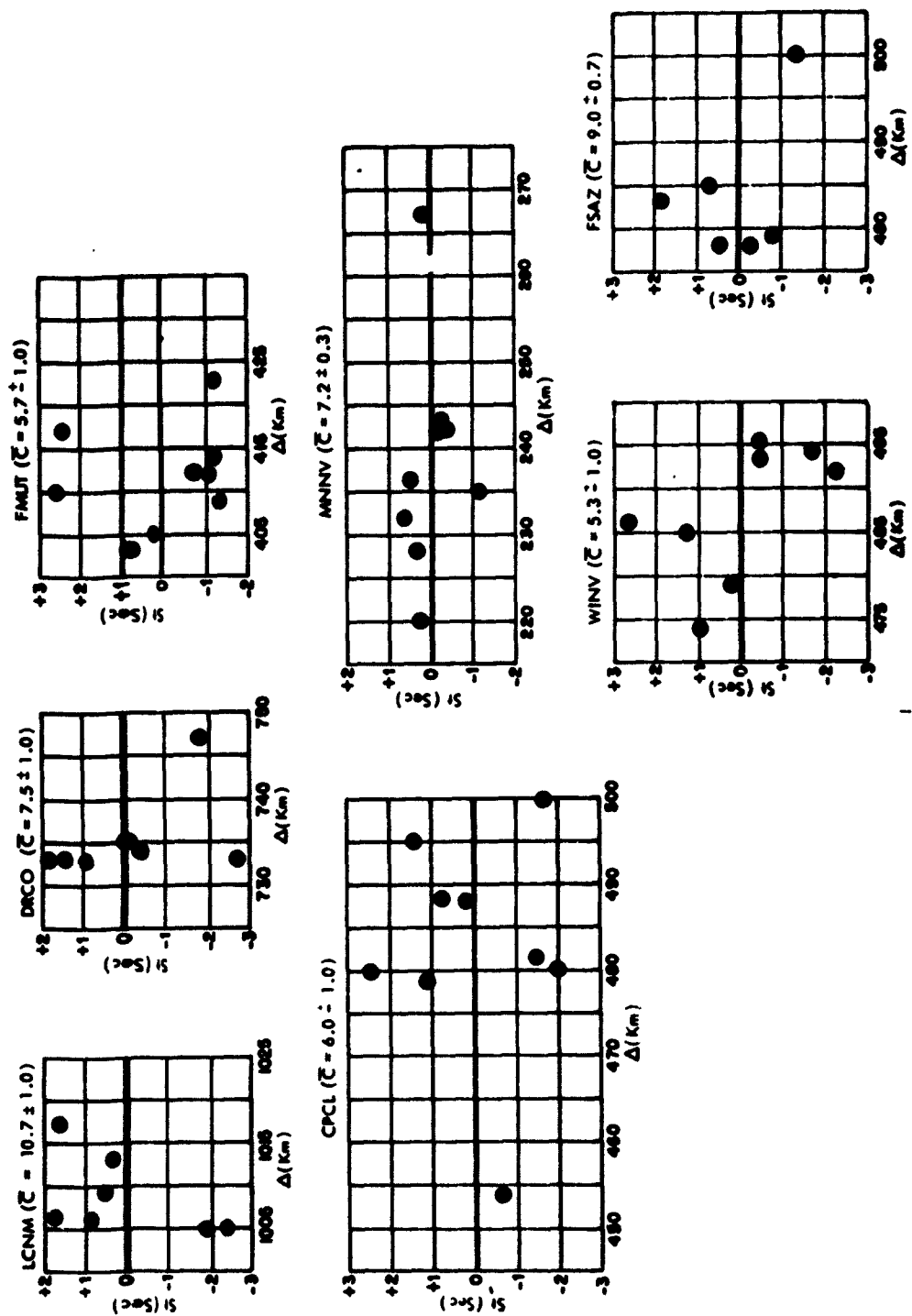the relation $\overline{K} = \dfrac{1}{N} \sum\limits_{i=1}^{N} \left[0.35 \, (Sg-Pg)_i - (Pg - Pn)_i \right]$

FIGURE 2. Pg-Pn Residuals from Average as a Function of Epicentral Distance, Δ

$$\bar{C} = \frac{1}{N} \sum_{i=1}^{N} \left[\frac{1}{27} \Delta_i - (Pg-Pn)_i \right]$$

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